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GLACIAL LAKE OUTBURST FLOODS IN THE PAMIR OF TAJIKISTAN: CHALLENGES IN PREDICTION AND MODELLING

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ABSTRACT

Glacial lake outburst floods (GLOFs) are potentially highly dangerous events and have contributed to numerous disasters in history. Today, computer models are standard tools to estimate the magnitude of hazardous events in the future and to support risk mitigation. The present paper explores the potentials and limitations of modelling for predicting the motion of potential future GLOF events, based on examples from the Pamir (Tajikistan). Since the flow behaviour of GLOFs is in between debris flows and floods, different model approaches come into consideration, though none of them is perfectly suitable for GLOFs. RAMMS as a mass movement model and FLO-2D as a river hydraulics model were employed comparatively for the same areas. The friction parameters for RAMMS and rheologic parameters for FLO-2D were first calibrated by back-calculation with the well-documented Dasht event from summer 2002, and then applied to other areas. However, the applicability of such parameters to GLOFs of different volume and over a different topography remains questionable. The results may nevertheless be a valuable input for risk mitigation efforts, but due to the complex nature of GLOFs and the connected uncertainties, particular care is required when interpreting the model results. The critical points and potential approaches to deal with the limitations are discussed in the paper.

KEY WORDS: *glacial lake outburst floods (GLOFs), modelling, Central Asia*

INTRODUCTION

Natural dams of different size and origin do exist in mountain areas all over the world (COSTA & SCHUSTER, 1988). They often retain lakes which, in the case of a dam failure, may drain as powerful floods. If the outbursting lake is located within the glacial or periglacial area, such events are called Glacial Lake Outburst Floods (GLOFs). They can evolve in different ways (Fig. 1), for example:

- rock/ice avalanches or calving glaciers that produce flood waves in a pro-, supra- or periglacial lake which may overtop and breach glacial or morainic dams (TINTI *et alii*, 1999);
- rising pro-, supra-, sub- or periglacial lake levels, leading to overflow, progressive incision or mechanical rupture of a moraine or ice dam, as well as to retrogressive erosion of a moraine dam;
- enhanced ground water flow (piping) through moraines, or hydrostatic failure of ice dams which can cause sudden outflow of accumulated water (ITURRIZAGA, 2005a; 2005b);
- degradation of glacier dams or ice-cores in morainic dams leading to loss of stability and to subsidence resulting in internal failure or progressive erosion if a certain threshold is reached.

RICHARDSON & REYNOLDS (2000) provide an overview of failure mechanisms and case studies. GLOFs often have a highly destructive potential because a large amount of water is released within a short time, with a high capacity to erode loose debris, potentially leading to a powerful flow with a long travel distance. Peak discharges are often some magnitudes higher than in the case of "normal" floods (Cenderella & Wohl, 2001). The source area is usually far away from the area of impact and events occur at very long time intervals or as singularities, so that the population at risk is often not prepared for such events (Schneider *et alii*, 2004). Deficiencies in risk communication are often responsible that events evolve into disasters (Carey, 2005). A number of significant GLOFs resulting in fatalities and severe damage have occurred during the previous decades, particularly in the Himalayas, the mountains of Central Asia, the North American mountains, New Zealand, and the Alps. Case studies are provided e.g. by Clarke (1982); Hewitt (1982); Watanabe & Rothacher (1996); Richardson & Reynolds (2000); Schneider *et alii* (2004) and Vilimek *et alii* (2005). Climate change, with its impact on the glacial extent, the hydrological cycle and the condition of ice-bearing dams, may condition the occurrence of GLOFs in manifold ways and on different time scales (Evans & Clague, 1994; Dussaillant, 2009).

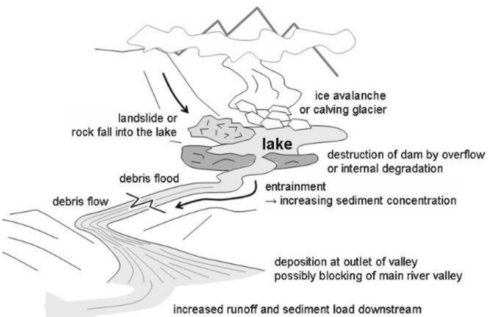

Fig. 1 - Schematic representation of a glacial lake outburst flood (GLOF)

The present paper deals with computer modelling of the flow path of GLOFs. Using test areas in the Pamir (Tajikistan), the general potentials and limitations of such approaches as well as the suitability of different model concepts are explored and discussed. Particular emphasis is put on the capabilities of the models for the prediction of future events.

BACKGROUND

In summer 2002, the village of Dasht (Shakhdara Valley, Pamir, Tajikistan; Fig. 2a) was hit by a GLOF. 10 km upstream in the headwaters of the valley, a supra-glacial lake had suddenly released an estimated volume of 250,000 m³ of water (Schneider *et alii,* 2004). The volume of debris deposited on the cone was estimated 1.0-1.5 million m³, meaning that the ratio between entrained debris and water would be 4-6. This is a very high value compared to the ratio of 2-3 suggested by Huggel *et alii* (2004b). However, an even higher ratio than observed for Dasht was reported by Breien *et alii* (2008) for a GLOF in Norway. Possibly, subglacial water reservoirs connected to the superficial lake and highly saturated erodible material was involved in both events.

Fig. 2a - Left: The debris cone resulting from the GLOF in Dasht in summer 2002, covering most of the village and damming a small lake upstream
Fig. 2b - Right: Lake dammed by a rock glacier in the upper Khavrazdara Valley

It was reported that the flood wave arrived in Dasht in three stages, a phenomenon that can be explained by temporary backwater in the canyon of the lower transitional zone due to blockage of large boulders transported by the GLOF or by lateral slope failures followed by vigorous breakthroughs (Schneider *et alii*, 2004). The event destroyed a large portion of the village of Dasht, killed a few dozens of people, and dammed a small lake at the Shakhdara river. The event hit the village completely unexpected, as there was no awareness of the hazard and preparedness for the event.

Even though potentially hazardous supra-, pro- and periglacial lakes can be identified relatively easily with remote sensing tools and field work (e.g. Kaeaeb *et alii*, 2005; Quincey *et alii*, 2007), modelling and prediction of the motion and reach of GLOFs still remain a challenge. Like many other GLOFs, the characteristics of the Dasht event underwent pronounced changes during the flow, converting from normal runoff to a hyperconcentrated flow and finally to a granular debris flow. Changes in flow behaviour imply some difficulties when using computer models to predict the flow path and velocities of such events. Simple empirical rules for debris flows travel distances show a large scatter among themselves and generally underestimate the travel distance of GLOFs (Fig. 3). Corominas *et alii* (2003) assume an average runout angle of 21° for debris flows on unobstructed flow paths. Huggel *et alii* (2003), employing the Modified Single Flow direction model MSF, used an angle of 11° proposed by Haeberli (1983) as a minimum for observed granular debris flows. However, in the case of the Dasht event, both values underestimate the maximum travel distance of the debris flow which reached a runout angle as low as 9.3°. The debris flow actually did not stop before reaching the main valley. Rickenmann (1999) suggested the following empirical relationship for the travel distance of debris flows:

$$L = 1.9V^{0.16}Z^{0.83} \quad \text{Eq. 1,}$$

where L is the travel distance of the flow, V is the involved volume, and Z is the loss of elevation. Using the release volume of 250,000 m^3 in Eq. 1, the Dasht travel distance is again strongly underestimated, while the estimated deposition volume of 1.5 million m^3 leads to a travel distance closer to the observation.

However, it is not the 'fault' of these empirical models not to fully capture the Dasht event, but rather a conceptual problem related to the characteristics of the event: The GLOF - as many others - was not a classical debris flow, it was characterized by several flow transformations (hyperconcentrated to debris flow and back).

Semi-deterministic approaches, using a friction model (e.g. Perla *et alii*, 1980 for snow avalanches) in combination with random walk routing techniques go one step further than strictly empirical models and are often applied in combination with GIS (e.g. Gamma, 2000; Wichmann, 2006; Mergili *et alii*, 2008). They can be used for back-calculating GLOFs and other types of mass flows, but are only partly suitable for prediction purposes. Reliable physically based dynamic models are therefore required when trying to predict the motion of potential future mass flows (Hungr *et alii,* 2005).

Several physically based model approaches and software packages are potentially suitable for GLOF runout modelling, some of which were developed within the mass movement research community, others within the river hydraulics community.

Many mass movement models go back to the Voellmy (1955) approach and were developed for snow avalanches, but are also applicable to other types of mass movements. A remaining problem is the entrainment of material that is an important characteristic of GLOFs (Breien *et alii*, 2008; Xu, 1988). Some models include entrainment modules, but rather on an empirical-statistical than on a physical base. Breien *et alii* (2008) emphasize the lack of appropriate data and knowledge on entrainment issues.

River hydraulics models commonly use flood routing algorithms based on volume conservation and a roughness parameter (usually Manning's n) for estimating the extent and the depth of river flow and flooding events. Most of the widely used software packages (e.g. FLO-2D, HecRAS) include modules for sediment transport, hyperconcentrated flows, and debris and mud flows. In contrast to mass movement models, they require input hydrographs. Therefore, they allow accounting more detailed for the onset mechanism, which plays a crucial role for the flow propagation and the magnitude of the resulting flood wave (Walder & Costa, 1996). This type of model is particularly better suited for modelling the initial stage and flow path section of the event that depends more strongly on the input hydrograph. Bertolo & Wieczorek (2005) compare models following different concepts for the same set of debris flows. For an appropriate modelling of the motion of GLOFs, a combination of mass movement and river hydraulics models is suggested.

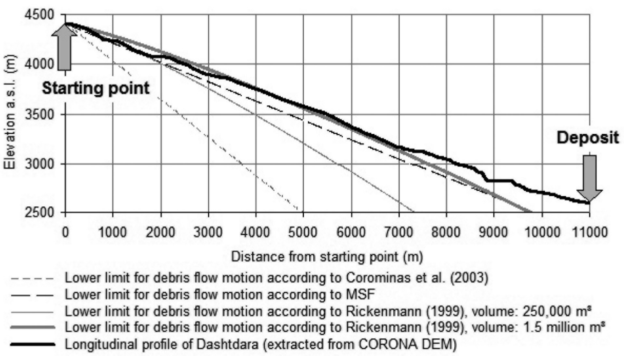

Fig. 3 - Empirical approaches developed for the reach of debris flows and the observed travel path of the Dasht 2002 event

OBJECTIVES

The general objective of the study presented was to elaborate a way to estimate the travel distance and travel times of potential future GLOFs by comparing the results of two different models for mass flows. Each of them partially represents certain characteristics of GLOFs but cannot fully reproduce the flow behaviour. The results and the model settings and parameters suitable for GLOFs, but also the needs for further research and model development are high-lighted, using examples from the Pamir (Tajikistan).

The paper concentrates on the movement of the flood wave itself, the breaching process of the dam is not considered. For the on-set of the GLOF process, scenarios for the outburst volume and hydrograph, as well as for the finally deposited volume (including entrained debris) were elaborated. The scenarios are based on the lake volume, the dam characteristics, and the susceptibility to rock and ice avalanches into the lake.

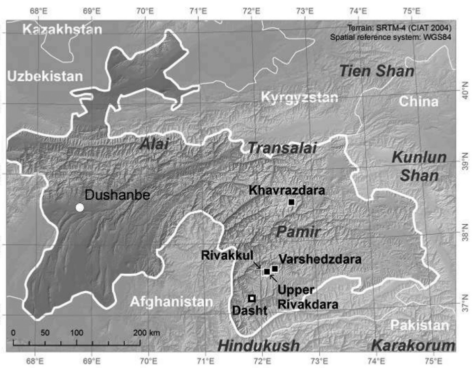

Fig. 4 - Map of Tajikistan with the five selected areas for modelling

STUDY AREAS AND DATA

The modelling was performed for five study areas in Tajikistan (one for back-calculation, four for prediction; Fig. 4). All areas are located in the Pamir, a heavily glaciated high mountain area culminating in 7,495 m a.s.l. The lakes used in the case studies are distributed between 3,800 m and 4,800 m a.s.l.

The results for Khavrazdara, a Northern tributary of the Bartang Valley, will be discussed in detail below. 20 km upstream from the valley outlet, the tongue of a rock glacier dams a lake with a surface of 2 km², approximately, and an estimated volume of 40 million m³ (Fig. 2b). In the case of a climate-change-induced degradation of the rock glacier tongue, a breach of the dam followed by a flood wave down the valley is possible.

The following information was compiled for Khavrazdara as well as for all the other case studies:

- DEMs of different resolution were prepared for the investigation areas in order to allow the determination of the effect of resolution. SRTM-4 (90 m) was used as well as 10 m and 20 m DEMs derived from CORONA imagery and 5 m DEMs derived from WorldView1 imagery.
- Susceptible glacial lakes were identified using analysis of multitemporal satellite imagery, helicopter surveys, and field investigations. The surface of the relevant lakes was computed using ASTER imagery and the lake volumes were estimated.
- The peak discharges of potential outburst events were estimated from empirical rules (Evans 1986; Costa, 1988; Costa & Schuster, 1988; Manville, 2001; Huggel *et alii*, 2004a). Scenarios of outburst hydrographs were then created, based on the estimated peak discharge and the lake volume.
- The characteristics of the flow path and the area of deposition were mapped from satellite imagery, from the helicopter, and in the field (morphology of the valley, type of surface material, indicators for former outburst flood events).

METHODS

The first model used is the physically based mass movement model RAMMS (Rapid Mass Movements), developed at the WSL Institute for Snow and Avalanche Research SLF Davos, Switzerland (see Christen *et alii*, 2010a, 2010b for a more detailed description and for case studies). The frictional resistance S is based on the Voellmy (1955) model that combines dry Coulomb friction μ with a velocity-squared dependent turbulent friction ξ.

$$S = \mu H g \cos\varphi + \frac{gU^2}{\xi} \qquad \text{Eq. 2}$$

where g is the gravitational acceleration, H is the flow depth, φ the slope angle, and U is the depth-averaged flow velocity. The maximum velocity U_{max} is defined by Voellmy (1955) as:

$$U_{\max} = \sqrt{\xi H (\sin\varphi - \mu\cos\varphi)} \qquad \text{Eq. 3}$$

If μ equals zero, Eq. 3 can be further transformed into the Chézy equation. Therefore, by applying low μ-values, an approximation to turbulent clear water open channel flow can be established.

RAMMS was originally designed to predict the maximum travel distance and velocity of snow avalanches. Calibrated parameters are available for this type of process. They are only valid for the front of the avalanche, so that the deposition geometry cannot be predicted in a straightforward way (Christen *et alii*, 2010a). The model is able to compute entrainment of material by the flow, governed by an empirically determined scaling factor and an entrainment law. RAMMS has recently been used for modelling other types of mass movements. Schneider *et alii* (accepted) successfully used it for the back-calculation of large rock-ice avalanches and Preuth *et alii* (in press) simulated various large rock avalanches in the European Alps. It has further been used for the simulation of debris flows in Switzerland (Naef *et alii*, 2006; Rickenmann *et alii*, 2006; Armento *et alii*, 2008) but not yet for modelling GLOFs.

The second model - FLO-2D - was developed by J. O'Brien (e.g. O'Brien *et alii*, 1993; O'Brien, 2001). It is a volume conserving model for flow routing of clear water floods, hyperconcentrated flows, or debris flows over floodplains or through confined channels. Topography, input hydrograph, and resistance to flow determine the flow behaviour. Case studies are provided e.g. by Huebl & Steinwendtner (2001) or Bertolo & Wieczorek (2005). For clear water flow, the governing equations are:

$$\frac{\partial h}{\partial t}+\frac{\partial hU}{\partial x}=i \qquad \text{Eq. 4,}$$

$$S_f=\alpha-\frac{\partial h}{\partial x}-\frac{U}{g}\frac{\partial U}{\partial x}-\frac{1}{g}\frac{\partial U}{\partial t} \qquad \text{Eq. 5,}$$

where h is the flow depth, U is the depth-averaged flow velocity in one flow direction x, i is rainfall intensity, S_f is the friction slope component (based on Manning's Equation), and α is the bed slope.

Both programs - RAMMS and FLO-2D - need a DEM as input. RAMMS further requires the spatial distribution and depth of the release volume, the coefficients and possible areas for entrainment, and the friction parameters μ and ξ. FLO-2D needs an input hydrograph and values of Manning's n. When using FLO-2D for debris flow modelling the rheologic flow parameters viscosity and yield stress must be specified.

The following work flow was applied for the modelling:

1. Back-calculation of a well-documented recent GLOF: the Dasht event from summer 2002 was used to test the models and to find suitable parameter values. Travel distance, the spatial distribution of the deposit, and the travel time from the start to the deposit were used as reference for the calibration;
2. Scenarios of possible future outburst events of selected lakes (see Table 1 for an example) were elaborated. Outburst volumes, peak discharges, and flow rheologies were varied among the different scenarios. The friction parameters of RAMMS with the best fit for Dasht were taken as a reference, but adapted according to the outburst volumes and water content so that the worst case scenario reached the former debris flow fan of the main valley (compare Discussion and Conclusions).
3. The scenarios were run with RAMMS and FLO-2D. The resolution of the DEM and the computation were varied in order to estimate the influence of this setting on the model results.

RESULTS

BACK-CALCULATION FOR DASHT

First, the Dasht (2002) event was back-calculated using RAMMS (Fig. 5). The purpose was to calibrate the model for this type of event and to find suitable values for the friction parameters μ and ξ. The model was run on the CORONA DEM (10 m), and on the SRTM-4 DEM (90 m) with a calculation resolution of 20 m in order to figure out the influence of different levels of smoothing of the terrain.

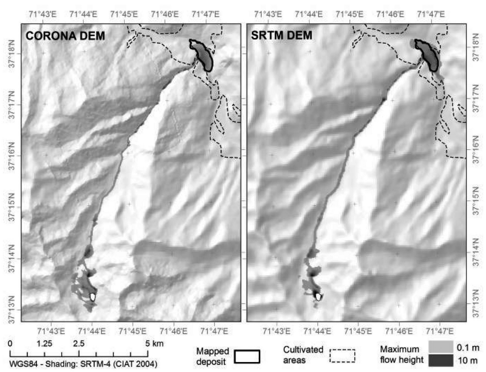

Fig. 5 - Back-calculation of the Dasht 2002 event using RAMMS

Friction parameters of $\mu = 0.14$ and $\xi = 1{,}300$ proved to be the best guess for reconstructing the event, though it was necessary to assume lower values of μ (0.01) and higher values of ξ (2,000) in the flat starting area (representing the lake surface) in order to initiate the movement. The velocities and the extent of spreading in the area of deposit were larger when using the SRTM DEM (smoother terrain).
The simulated travel time from the onset of the flow to the village was 55 minutes with the SRTM DEM and 76 minutes with the CORONA DEM. These values correspond reasonably with local reports concerning the time difference between the acoustic detection of the GLOF and its arrival at the village.

As the GLOF event in Dasht propagated as a debris flow, this case study was used to define the rheologic parameters for debris flow modelling in FLO-2D. It was found that values for viscosity $\eta = 279$ poises and yield stress $\tau = 798$ dynes/cm^2 represented best the debris flow in Dasht. Consequently these values were also used in the scenario modelling. FLO-2D was run on the CORONA DEM only. The simulated travel time, flow heights and extent matched well with the field observations.

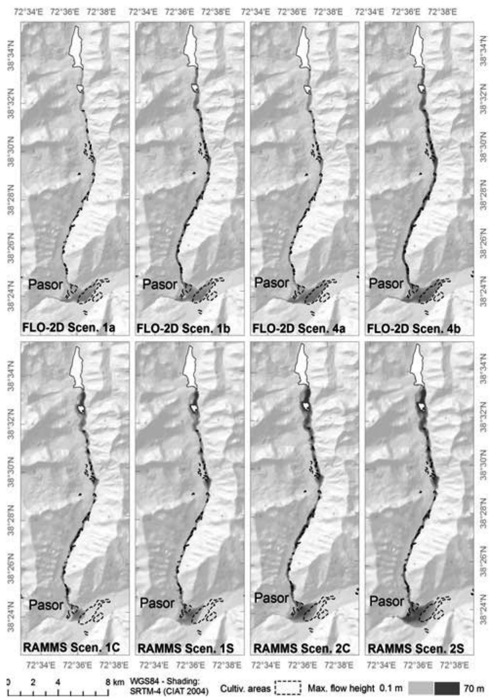

Fig. 6 - Maximum flow depth computed with FLO-2D and RAMMS for dif-ferent lake outburst scenarios of Khavrazdara

KHAVRAZDARA

Different scenarios for lake outburst floods were then computed for Khavrazdara, Varshedzdara, Upper Rivakdara, and Rivakkul (see Fig. 4). The modelling results for Khavrazdara (see Fig. 2b) are discussed in detail.

The scenarios defined for an outburst flood in Khavrazdara are shown in Table 1. A cell size of 20 m was used for the RAMMS simulations and 40 m for the FLO-2D simulations, respectively. Whilst the GLOFs simulated with FLO-2D reached the outlet of the valley, the RAMMS simulations indicated a stop of the flow in the middle portion of the valley when using the friction parameters calibrated with the Dasht event. It was then tested how much the friction would have to be reduced to allow the flow to reach the valley outlet and to cover the debris cone there. Friction values of $\mu = 0.04$ and $\xi = 1{,}000$ were found to be suitable. Decreased μ-values of $\mu = 0.03$ were used to account for the lower sediment concentration expected in the upper section (before entrainment takes place), whilst increased values of $\mu = 0.05$ were applied to account for the higher sediment concentration expected in the lower section. ξ-values were held constant for the entire flow path. The spatial distribution of the maximum flow height simulated with RAMMS and FLO-2D for selected scenarios is illustrated in Fig. 6.

With FLO-2D all scenarios were modelled as a hyperconcentrated flow with a volumetric sediment concentration of 20% on the one hand, and as a debris flow with volumetric sediment concentrations up to 50% on the other hand. Applying a range of different flow rheologies is a strategy to deal with the uncertainty regarding the flow type produced by the released water from a lake. The amount of water is the same in both flow types, but the debris flow is bulked with much more material. This is why its total flow volume and peak discharge are higher than for hyperconcentrated flows of the same outburst scenario. As the peak discharge has the highest influence on calculated maximum flow depths, and the higher viscosity results in lower flow velocities, inundation depths are higher when modelling the GLOF as a debris flow.

According to the simulation, the flow would reach the village of Pasor at the outlet of the valley between 48 minutes and 4.5 hours after the onset, depending on the scenario (see Table 1; average velocity between 1 and 6 m/s, respectively). This wide range shows the uncer-

Scenario	Starting volume	Deposition volume	Maximum discharge	Travel time
	10^6 m³	10^6 m³	m³/s	minutes
FLO-2D (all simulations on CORONA DEM)				
1a Hflw	15	19	2500	210
1b Dflw	15	23	4000	210
2a Hflw	15	20	10000	72
2b Dflw	15	25	16000	90
3a Hflw	30	38	2500	255
3b Dflw	30	47	4000	270
4a Hflw	30	38	10000	90
4b Dflw	30	48	16000	90
RAMMS				
1 C	15	45	N/A	99
1 S	15	45	N/A	73
2 C	30	90	N/A	70
2 S	30	90	N/A	48

Tab. 1 - Modelling of a potential GLOF from the large lake in the upper Khavrazdara: Scenarios, involved volumes, maximum discharge, and travel times to the village of Pasor (outlet of the valley). Hflw = Hyperconcentrated flow, Dflw = Debris flow, C = CORONA DEM , S = SRTM-4 DEM, N/A = not applicable

tainties connected to the scenarios, topographic data and parameters used. The maximum velocity ranges around 10 m/s over most of the valley, with much higher values yielded in the upper portion, particularly by RAMMS. The influence of the DEM resolution on the model results is considerable: finer DEM resolutions generally lead to a rougher surface which significantly reduces the flow velocity and hence the reach of the debris flow (see also Christen *et alii*, 2010a). The smoother the original terrain is, the less this effect is observed.

DISCUSSION AND CONCLUSIONS

The present study illustrates that modelling of GLOFs remains a challenge. Each case study area has its individual characteristics and the results provided by different model approaches sometimes diverged considerably. These differences are not surprising as the two models follow disparate concepts, each requiring a specific definition of the initial conditions (sudden release of mass vs. discharge curve). In order to homogenize the results and to account for the generally larger amount of water, the friction parameters used in RAMMS had to be reduced considerably in comparison to those used for the Dasht event. This is of very high importance when the results are interpreted or shown to local authorities. However, adapting the friction parameters individually for each study area in a way that the simulated flow reaches the area of interest (often the valley outlet) provides useful information in two ways:

- A comparison of the assumed friction parameter values with those derived from the back-calculation of documented events allows an assessment of how realistic the assumed parameters are, and therefore the likelihood of the flow to reach the outlet of the respective tributary valley. Table 2 shows the friction parameters used in the RAMMS calculation, based on the assumption that the flow would reach the outlet of the respective valley.
- Approximate travel times to the outlet can be derived, given that the assumed parameters are considered as realistic.

A special characteristic of the RAMMS model is the sudden release of the start volume (mass), that well represents a sudden mechanical failure of a lake dam or the overtopping of a large impact wave. However, this is not always the way how GLOFs are triggered and may therefore lead to exaggerated flow heights and widths in the upper flow section. In contrast, the ability to erode material from the ground is an important feature of RAMMS because it accounts for the often observed fact that start and end volumes differ significantly (Berti *et alii*, 1999, Breien *et alii*, 2008).

In general, RAMMS predicts higher values of flow depth in the uppermost section of the flow path than FLO-2D. This is due to the sudden release of the mass (see above). FLO-2D makes use of an input hydrograph that distributes the release volume over a given time period, leading to lower flow depths for given total volumes. This can better reproduce a dam failure due to progressive incision.

RAMMS predicts the stop of the flow and the deposition of the mass on the debris cone whilst FLO-2D tends to predict a continuation of the flow along the stream path of the main valley. The potential impact areas derived with RAMMS are therefore smaller and the inundation depths are larger than those calculated with FLO-2D.

Partially good correspondence is found in the flow durations to the outlet of the valley. Table 1 shows that the range of the flow durations calculated with RAMMS are similar to those derived from the FLO-2D calculations, at least regarding the - more critical - lower boundary. This is remarkable because they are computed completely independently (the adaptation of μ and ξ is a purely frictional issue).

Area	Volume	L	ΔZ	φ_{avg}	μ	ξ
	10^6 m³	m	m	degree		
Dasht	0.25[a], 1.50[b]	11,000	1,800	9.8	0.14	1,300
Khavrazdara	15 – 30[a], 45 – 90[b]	19,000	1,050	3.2	0.03*, 0.04**, 0.05***	1,000
Varshedzdara Lower Lake	0.5 – 1[a], 1.5 – 3[b]	11,500	1,350	6.7	0.09	1,350
Varshedzdara Upper Lake	2 – 5[a], 6 – 15[b]	13,500	1,650	7.0	0.08*, 0.10**, 0.12***	1,500*, 1,250**, 1,000***
Upper Rivakdara	0.37 – 0.73[a], 0.82 – 1.6[b]	4,800	700	8.3	0.08*, 0.09**, 0.10***	1,500*, 1,350**, 1,200***
Rivakkul	9.4 – 23.3[a], 31.6 – 58.5[b]	26,000	1,300	2.9	0.03	1200

*Tab. 2 - Involved volumes, valley characteristics, and friction parameters chosen for the RAMMS simulation. L = length of valley; ΔZ = loss of elevation; φ_{avg} = average inclination. [a] start volume [b] end volume * 1st section of flow path (upper) ** 2nd section of flow path (middle) *** 3rd section of flow path (lower)*

One has to conclude that, considering all relevant aspects, the simulation of the motion of potential future GLOFs remains a big challenge. Problems are in particular:

- The knowledge about the onset of the process is often limited (properties of dam, type of dam breach, understanding of process chains and interactions).
- The volume of water involved in the outburst flood is unclear. The lake bathymetry is often unknown and may change rapidly, whilst the ratio of water actually bursting out has to be estimated. Furthermore many lakes burst out within a short time after their development without being detected as potential source of hazard (Narama *et alii*, 2010). Continuous monitoring is required to keep updated on the existing hazards.
- Uncertainties related to erosion and deposition are a big unresolved issue. Erosion of the dam and the bed as well as concomitant deposition can strongly change the rheology and the moving volume of the flow. These changes have a direct impact on the spreading and reach.
- The flow transformation processes of the natural phenomena are a challenge for the models (and in general for any assessment). Software developed by the hydrological community is specialized to simulate floods or hyperconcentrated flows with input hydrographs on moderately steep flow channels and with lower sediment loads. In contrast to this, programs for rapid mass movements are better suited for steeper slopes and sudden failure of the initial volume. The typical characteristics of GLOFs are in between and vary for different channel sections. Sediment transport models properly computing erosion and deposition are rather designed for less steep slopes, so that they are hardly applicable to GLOFs. Furthermore, the outburst scenario is very critical. Flood dynamics are quite well understood and model results can therefore be considered as confident. In contrast, debris flow modelling is a based on empirical components and the results are therefore more inaccurate compared to modelling pure water or hyperconcentrated flows.

Nevertheless it is important not to model only the outburst scenarios as hyperconcentrated flows, but also as debris flows. With such a modelling strategy a range of expectable flow rheologies can be covered. This increases the robustness of the results and does not pretend a wrong accuracy.

Existing programs also largely fail to simulate process interactions and transformations such as the development of a hyperconcentrated flow into a debris flow, the effects of multiple flood waves (including the modified topography after the first wave), or the effects of short-term storage of water and debris by self-induced blockage of the valley.

Considering all these points, it has to be concluded that up to now, no well suitable modelling approaches do exist for GLOFs, as these represent highly variable phenomena and often exhibit a behaviour in between debris flows and floods. However, applying a combination of different model approaches, as attempted in the study presented, helps to estimate realistic process magnitudes, areas of impact, maximum velocities, and travel times. As a general conclusion for any kind of modelling effort, a responsible interpretation of the results and a controlled knowledge transfer to local authorithies is crucial.

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REFERENCES

Armento M.C., Genevois R. & Tecca P.R. (2008) - *Comparison of numerical models of two debris flows in the Cortina d'Ampezzo area, Dolo-mites, Italy*. Landslides, **5**: 143-150.

Berti M. & Simoni A. (2007) - *Prediction of debris flow inundation areas using empirical mobility relationships*. Geomorphology, **90**: 144-161.

Berti M., Genevois R., Simoni A. & Tecca P.R. (1999) - *Field observations of a debris flow event in the Dolomites*. Geomorphology, **29**: 265-274.

Bertolo P. & Wieczorek G.F. (2005) - *Calibration of numerical models for small debris flows in Yosemite Valley, California, USA*. Nat. Haz. Earth Syst. Sci., **5**: 993-1001.

Breien H., De Blasio F.V., Elverhoi A. & Hoeg K. (2008) - *Erosion and morphology of a debris flow caused by a glacial lake outburst flood, Western Norway*. Landslides, **5** (**3**): 271-280.

Carey M. (2005) - *Living and dying with glaciers: people's historical vulnerability to avalanches and outburst floods in Peru.* Glob. Plan. Change, **47**: 122-134.

Cenderelli D.A. & Wohl E.E. (2001) - *Peak discharge estimates of glacial lake outburst floods and "normal" climatic floods in Mount Everest region, Nepal*. Geomorphology, **40**: 57-90.

Christen C., Bartelt P. & Kowalski J. (2010a) - *Back calculation of the In den Arelen avalanche with RAMMS: interpretation of model results*. Ann. Glac., **51** (**54**): 161-168.

Christen M., Kowalski J. & Bartelt, B. (2010b) - *RAMMS: Numerical simulation of dense snow avalanches in three-dimensional terrain*. Cold Reg. Sci. Technol., **63**:1-14.

CIAT (International Centre for Tropical Agriculture) (2004) - *Void-filled seamless SRTM data V1, available from the CGIAR-CSI SRTM 90 m Database*. http://srtm.csi.cgiar.org

Clarke G.K.C. (1982) - *Glacier outburst floods from 'Hazard Lake,' Yukon Territory, and the problem of flood magnitude prediction*. J. Glac, **28** (**98**): 3-21.

Corominas J., Copons R., Vilaplana J.M., Altamir J. & Amigó J. (2003) - *Integrated Landslide Susceptibility Analysis and Hazard Assessment in the Principality of Andorra*. Nat. Haz., **30**: 421-435.

Costa J.E. & Schuster R.L. (1988) - *The formation and failure of natural dams.* Geol. Soc. Am. Bull., **7**: 1054-1068.

Costa J.E. (1988) - *Floods from dam failures.* In: Baker V.R. (1988, ed.) - *Flood Geomorphology*: 439-463, Wiley, New York.

Dussaillant A., Benito G., Buytaert W., Carling P., Meier C. & Espinoza F. (2009) - *Repeated glacial-lake outburst floods in Patagonia: an in-creasing hazard?* Nat. Haz., DOI 10.1007/s11069-009-9479-8.

Evans S.G. & Clague J.J. (1994) - *Recent climatic change and catastrophic geomorphic processes in mountain environments.* Geomorphology **10** (**1-4**): 107-128.

Evans S.G. (1986) - *The maximum discharge of outburst floods caused by the breaching of man-made and natural dams*. Can. Geotech. J., **23**: 385-387.

Frey H., Haeberli W., Linsbauer A., Huggel C. & Paul F. (2010) - *A multi-level strategy for anticipating future glacier lake formation and asso-ciated hazard potentials*. Nat. Haz. Earth Syst. Sci., **10**: 339-352.

Gamma P. (2000) - *dfwalk - Ein Murgang-Simulationsprogramm zur Gefahrenzonierung*. Geographica Bernensia G66. 144 pp. [in German].

Haeberli W. (1983) - *Frequency and characteristics of glacier floods in the Swiss Alps*. Ann. Glac., **4**: 85-90.

Hewitt K. (1982) - *Natural dams and outburst floods in the Karakorum Himalaya*. In: Glen J.W. (1982, ed.) - *Hydrological aspects of alpine and high-mountain areas*. IAHS Publication **138**: 259-269.

Huebl J & Steinwendtner H. (2001) - *Two-dimensional simulation of two viscous debris flows in Austria*. Phys. Chem. Earth (C), **26**: 639-644.

Huggel C., Haeberli W., Kaeaeb A., Bieri D. & Richardson S. (2004a) - *An assessment procedure for glacial hazards in the Swiss Alps*. Can. Geotech. J., **41**(**6**): 1068-1083.

Huggel C., Kaeaeb A. & Salzmann N. (2004b) - *GIS-based modeling of glacial hazards and their interactions using Landsat-TM and IKONOS imagery*. Norsk Geografisk tidsskrift / Norwegian J. Geogr., **58**: 761-773.

Huggel C., Kaeaeb A., Haeberli W. & Krummenacher B. (2003) - *Regional-scale GIS-models for assessment of hazards from glacier lake out-bursts: evaluation and application in the Swiss Alps*. Nat. Haz. Earth Syst. Sci., **3**: 647-662.

HUNGR O., COROMINAS J. & EBERHARDT E. (2005) - *State of the Art paper: Estimating landslide motion mechanism, travel distance and velocity*. In: HUNGR O., FELL R., COUTURE R., EBERHARDT E. (2005, eds.) - *Landslide Risk Management. Proceedings of the International Conference on Landslide Risk Management, Vancouver, Canada, 31 May - 3 June 2005*, 129-158.

IPCC (2007) - *Climate Change 2007: Synthesis Report, Intergovernmental Panel on Climate Change*, 26-73.

ITURRIZAGA L. (2005a) - *Historical Glacier-dammed Lakes and Outburst Floods in the Karambar Valley (Hindukush-Karakoram)*. GeoJournal, **62** (**3**-**4**): 1-47.

ITURRIZAGA L. (2005b) - *New observations on present and prehistorical glacier-dammed lakes in the Shimshal valley (Karakoram Mountains)*. J. Asian Earth Sci., **25** (**4**): 545-555.

IVERSON R.M., SCHILLING S.P. & VALLANCE J.W. (1998) - *Objective delineation of lahar-inundation hazard zones*. GSA Bull., **110** (**8**): 972-984.

KAEAEB A., HUGGEL C., FISCHER L., GUEX S., PAUL F., ROER I., SALZMANN N., SCHLAEFLI S., SCHMUTZ K., SCHNEIDER D., STROZZI T. & WEIDMANN Y. (2005) - *Remote sensing of glacier- and permafrost-related hazards in high mountains: an overview*. Nat. Haz. Earth Syst. Sci., **5**: 527-554.

MANVILLE V. (2001) - *Techniques for evaluating the size of potential dam-break floods from natural dams*. Institute of Geological and Nuclear Sciences Science Report 2001/28, 72 pp.

MERGILI M., FELLIN W., MOREIRAS S.M. & STOETTER J. (2008) - *Integrated modelling of debris flows in the Central Andes based on Open Source GIS*. Geophys. Res. Abstr., 10. [abstract]

NAEF D., RICKENMANN D., RUTSCHMANN P. & MCARDELL B.W. (2006) - *Comparison of flow resistance relations for debris flows using a one-dimensional finite element simulation model*. Nat. Haz. Earth Syst. Sci., **6**: 155-165.

NARAMA C., DUISHONAKUNOV M., KAEAEB A., DAIROV M. & ABDRAKHMATOV K. (2009) - *The 24 July 2008 outburst flood from western Zyndan glacier lake, Tien Shan, Kyrgyzstan*. Nat. Haz. Earth Syst. Sci., doi:10.5194/nhess-10-647-2010.

O'BRIEN J.S. (2001) - *FLO-2D Users Manual*. Nutrioso, Arizona. 83 pp. and appendices.

O'BRIEN J.S., JULIEN, P.Y. & FULLERTON W.T. (1993) - *Two-dimensional water flood and mudflow simulation*, J. Hydraul. Eng., **119**: 244-261.

PERLA R., CHENG T.T. & MCCLUNG D.M. (1980) - *A Two-Parameter Model of Snow Avalanche Motion*. Journal of Glaciology, **26**: 197-207.

PREUTH T., BARTELT P., KORUP O. & MCARDELL B.W. (in press) - *Fragmentation and frictional relaxation in rock avalanches*. J. Geophys. Res.

QUINCEY D.J., RICHARDSON S.D., LUCKMAN A., LUCAS R.M., REYNOLDS J.M., HAMBREY M.J. & GLASSER N.F. (2007) - *Early recognition of glacial lake hazards in the Himalaya using remote sensing datasets*. Glob. Plan. Change, **56** (**1**-**2**): 137-152.

RICHARDSON S.D. & REYNOLDS J.M. (2000) - *An overview of glacial hazards in the Himalayas*. Quatern. Int., **65**/**66**: 31-47.

RICKENMANN D. (1999) - *Empirical Relationships for Debris Flows*. Nat. Haz., **19**: 47-77.

RICKENMANN D., LAIGLE D., MCARDELL B.W. & HUEBL J. (2006) - *Comparison of 2D debris-flow simulation models with field events*. Computational Geosciences, **10**: 241-264.

SCHNEIDER D., BARTELT P., CAPLAN-AUERBACH J., CHRISTEN M., HUGGEL C., & MCARDELL B. W. (accepted) - *Insights into rock-ice avalanche dynamics by combined analysis of seismic recordings and a numerical avalanche model*. J. Geophys. Res.

SCHNEIDER J. F., GMEINDL M. & TRAXLER K. (2004) - *Risk Assessment of Remote Geohazards in Central and Southern Pamir/GBAO, Tajikistan*. Report to the Ministry of Emergency, Tajikistan and the Swiss Agency for Development and Cooperation (SDC).

TINTI S., MARAMAI A. & CERUTTI A.V. (1999) - *The Miage Glacier in the Valley of Aosta (Western Alps, Italy) and the extraordinary detachment which occurred on August 9, 1996*. Phys. Chem. Earth (A), **24** (**2**): 157-161.

VILÍMEK V., ZAPATA M.L., KLIMES J., PATZELT Z., & SANTILLÁN N. (2005) - *Influence of glacial retreat on natural hazards of the Palcacocha Lake area, Peru*. Landslides, **2** (**2**): 107-115.

VOELLMY A. (1955) - *Ueber die Zerstoerungskraft von Lawinen*. Schweizerische Bauzeitung, **73**: 159-162, 212-217, 246-249, 280-285. [in German].

WALDER J.S. & COSTA J.E. (1996) - *Outburst floods from glacierdammed lakes: the effect of mode of lake drainage on flood magnitude*. Earth Surf. Proc. Landforms, **21**: 701-723.

WATANABE T. & ROTHACHER D. (1996) - *The 1994 Lugge Tsho glacial lake outburst flood, Bhutan Himalaya*. Mt. Res. Dev., **16**: 77-81.